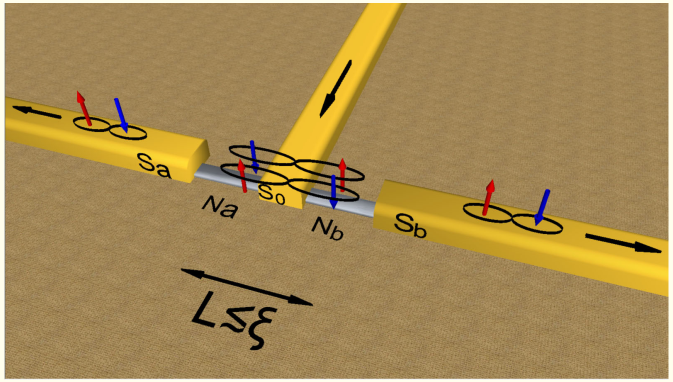
Cooper pairs in a multiterminal junction : from the Cooper pair splitter to quartets



Frank Hekking Memorial Les Houches Jan 2018

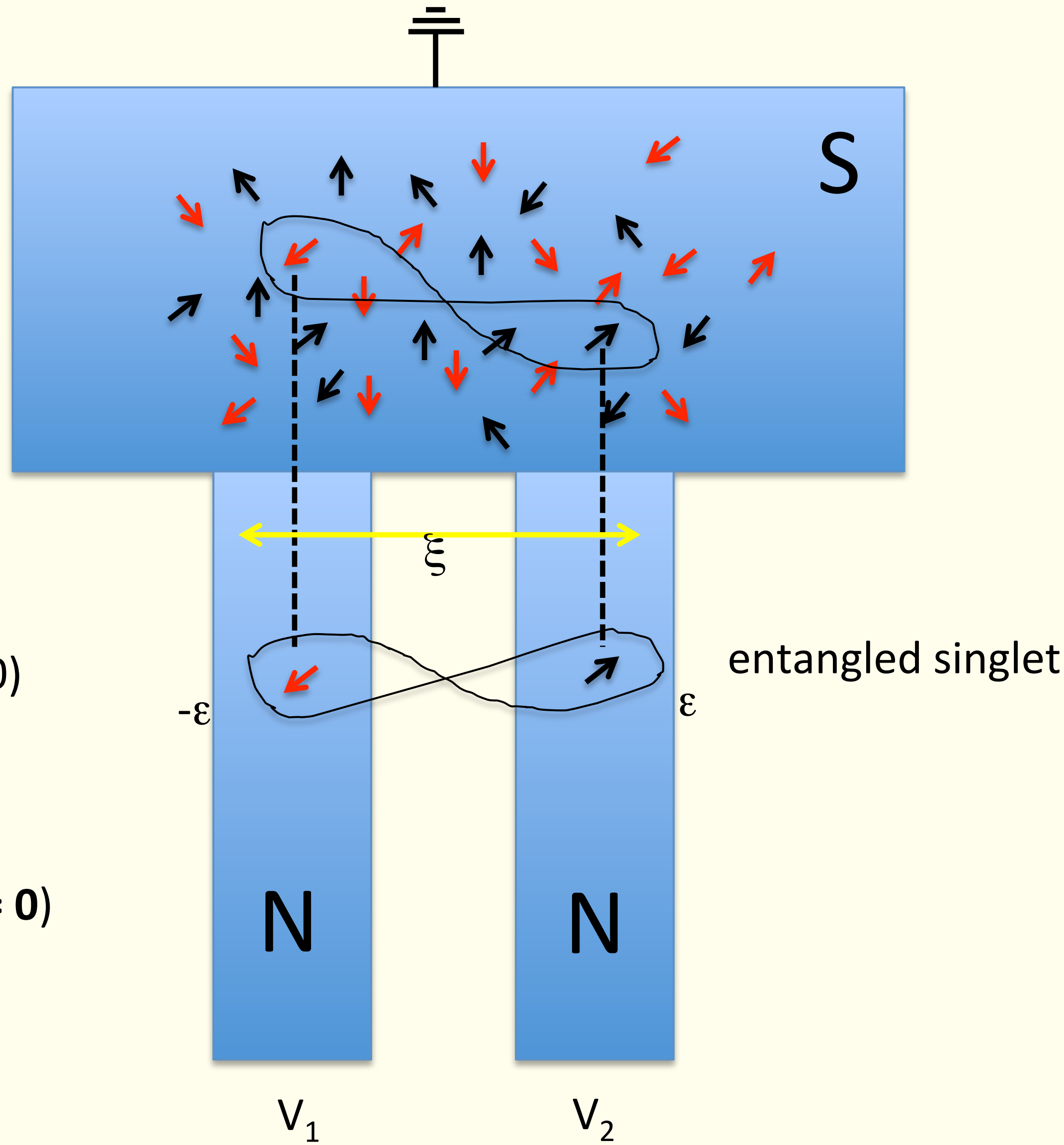
Cooper pair splitting in N-S-N setup

Non-local Andreev reflection, takes place on a length scale ξ

Requires a three-terminal structure

-Nonlocal magnetoresistance ($S_z = 0$)
-Nonlocal energy filtering
-Positive shot noise correlations

-Spin and energy entanglement (**S = 0**)
more elusive...



A brief (and incomplete) history of Cooper pair splitting

Byers, Flatté, PRL 199
Torrès, Martin, EPJB 1999
Deutscher, Feinberg, APL 2000
Choi, Bruder, Loss, PRB 2000

...many others 2000-2017

Nonlocal « crossed » Andreev reflection
from anomalous propagator in S

$$g^{12}(\boldsymbol{r},\omega) \sim \frac{e^{-\frac{r}{2\xi(\omega)}}}{2\pi r} \frac{\Delta}{\sqrt{\Delta^2-\omega^2}}$$

Nonlocal normal reflexion
« elastic cotunneling »
from normal propagator in S

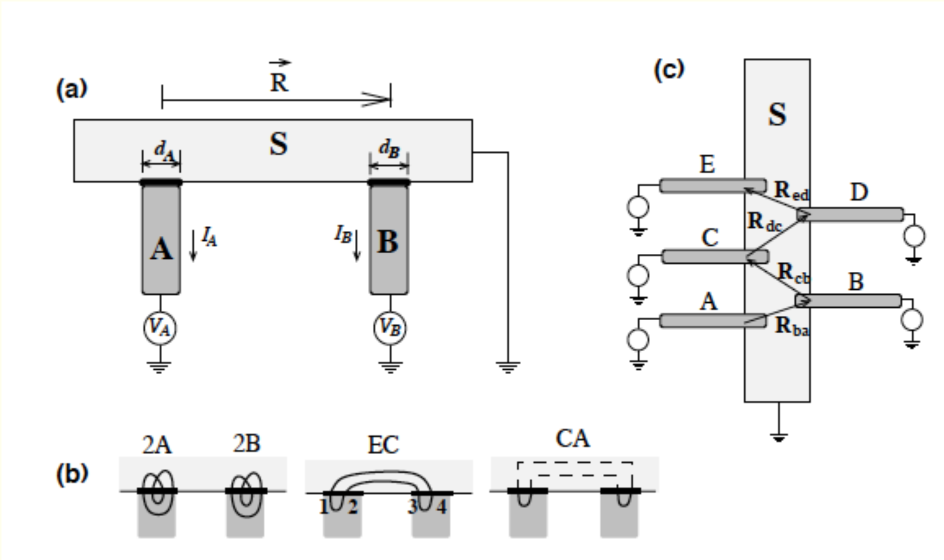
$$g^{11}(\boldsymbol{r},\omega) \sim \frac{e^{-\frac{r}{2\xi(\omega)}}}{2\pi r} \left(\frac{\omega \sin k_F r}{\sqrt{\Delta^2-\omega^2}} + \cos k_F r\right)$$

same microscopic origin : evanescent qp in S
competing processes in nonlocal conductance

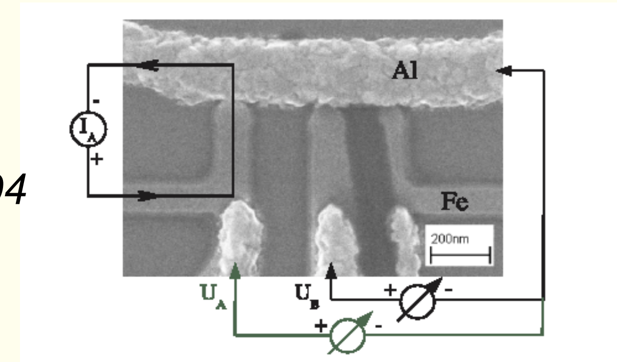
EUROPHYSICS LETTERS 15 April 2001
Europhys. Lett., **54** (2), pp. 255–261 (2001)

Correlated tunneling into a superconductor in a multiprobe hybrid structure

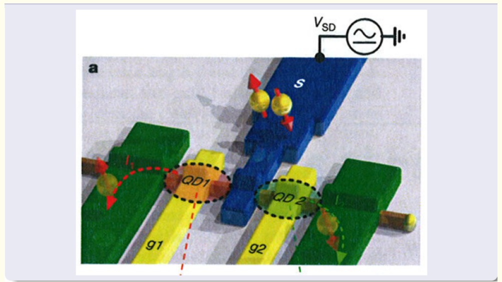
g
G. FALCI[1,2,3], D. FEINBERG[3] and F. W. J. HEKKING[4]



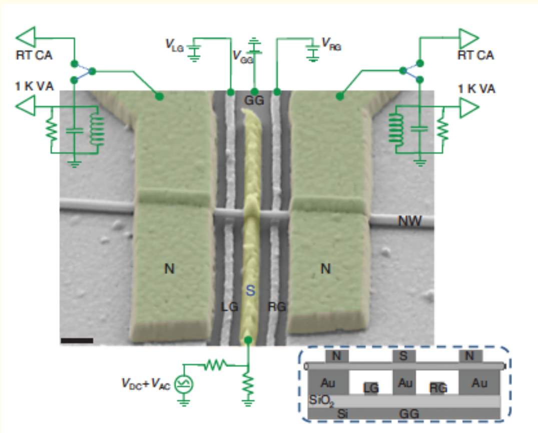
CPS Experiments

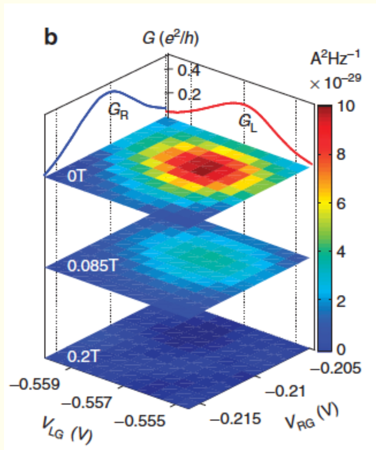


Beckmann et al., PRL 2004
(metal)

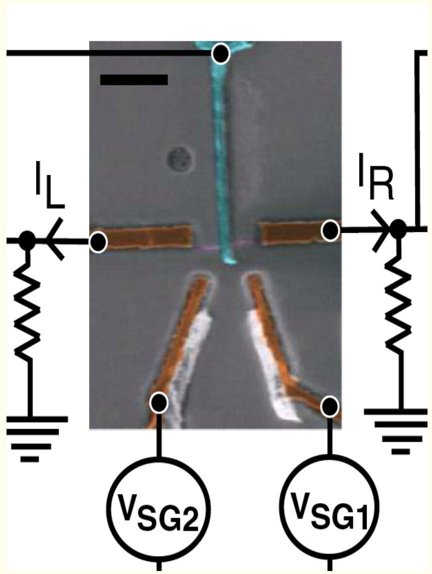


Schönenberger et al., Nature 2009 (nanowire)



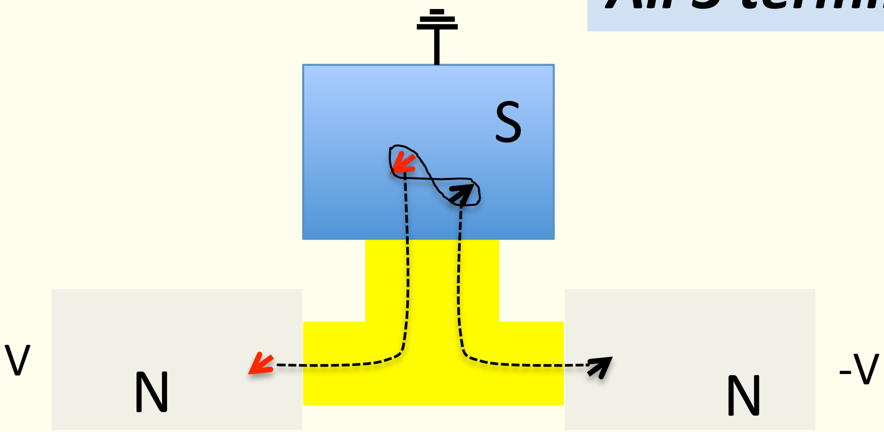


Das et al., Nature 2012 (nanowire)



Kontos et al., PRL 2009
(nanotube)

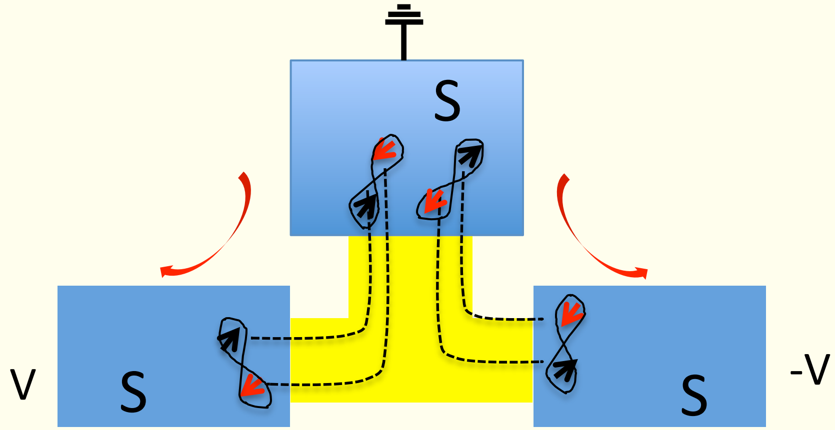
All 3 terminals superconducting...



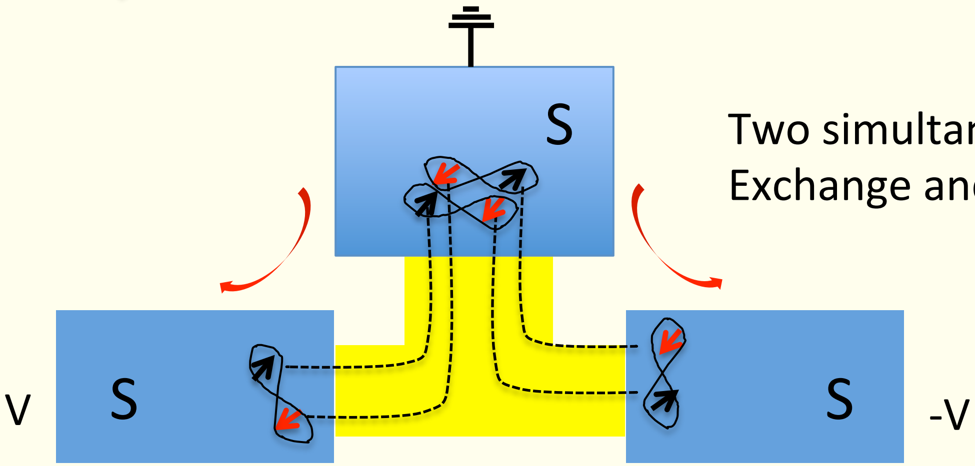
Cooper pair splitting...

Correlated Cooper pair transfers

Independent Cooper pair transfers



No CPS : ac Josephson processes !



Two simultaneous Cooper pair splittings
Exchange and recombination

dc mode ! QUARTETS

History of biased 3-terminal junctions

Cuevas, Pothier 2007
Houzet, Samuelsson 2010

Freyn, Douçot, D. F., Mélin PRL 2011
Jonckheere et al. PRB 2013
D.F. et al. EPJB 2015
Mélin et al. PRB 2016, EPJB 2016
Padurariu et al. PRB 2017

+ experimental works

Pfeffer, Duvauchelle, Courtois, Mélin, D.F., Lefloch PRB 2014
Cohen, Ronen, Kang, Heiblum, D.F., Mélin, Shtrikman (ArXiv)
Strambini, D'Ambrosio, Vischi, Bergeret, Nazarov, Giazotto Nat. Nanotech. 2016 (2-terminal)

Diffusive metallic junction

Equilibrium diffusive SNS junction

$$eI_c \approx G_N E_{Th}$$

G_N normal conductance
dc current destroyed by small V

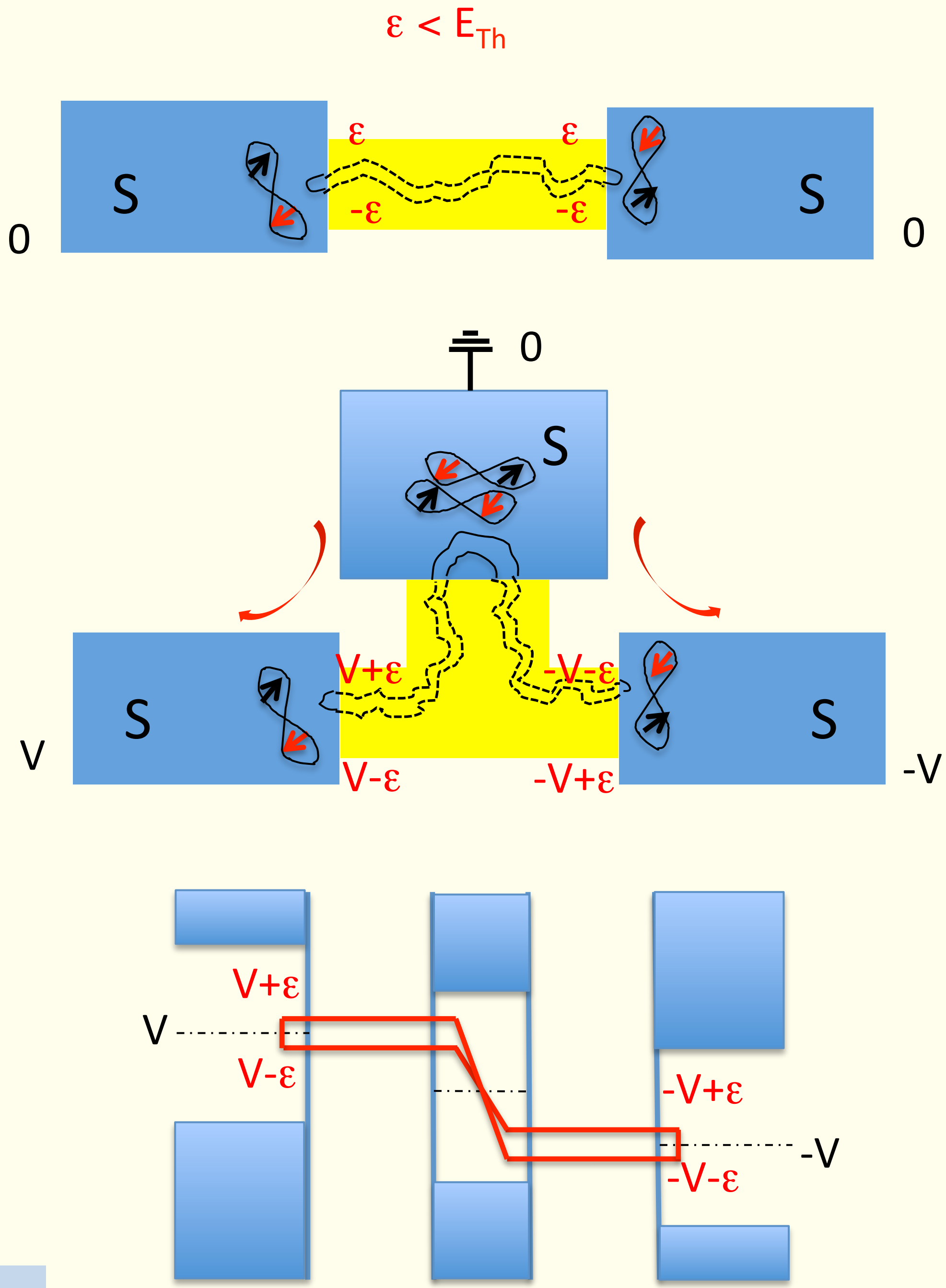
Three-terminal generalization

$$eI_Q \approx G_{CAR} E_{Th}$$

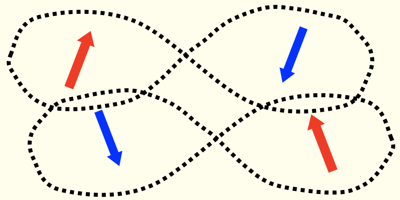
G_{CAR} crossed Andreev conductance

$\varepsilon < E_{th}$ but

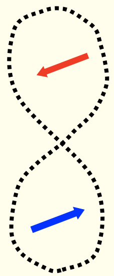
NO CONDITION ON VOLTAGE V !

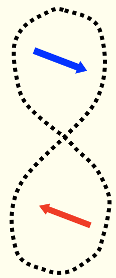


Exchange process → negative sign



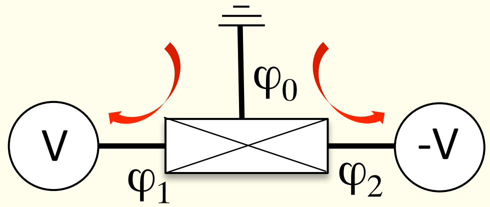
$$\frac{1}{\sqrt{2}}(d^\dagger_{a\uparrow}d^\dagger_{b\downarrow} - d^\dagger_{a\downarrow}d^\dagger_{b\uparrow}) \quad \text{x} \quad \frac{1}{\sqrt{2}}(d^\dagger_{a\uparrow}d^\dagger_{b\downarrow} - d^\dagger_{a\downarrow}d^\dagger_{b\uparrow})$$





$$-|\uparrow\ \downarrow\rangle_a\,|\downarrow\ \uparrow\rangle_b$$

Phase coherence : current / phase characteristics



$$\varphi_1(t) = \varphi_1 + 2eV\,t \;;\;\; \varphi_2(t) = \varphi_2 - 2eV\,t \;;\;\; \varphi_0 = 0$$

$\varphi_1 + \varphi_2 - 2\varphi_0$ constant of motion

A priori, in a tunnel limit, D.C.quartet current

$I_Q = - I_{Qc}\,(V)\;\; \sin\,(\varphi_1 + \varphi_2)$ controlled by voltage V

Two independent variables V and $\varphi_1 + \varphi_2$

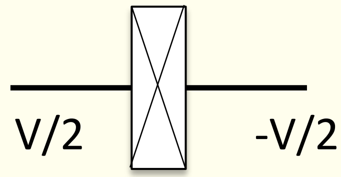
Intrinsic synchronization of ac components → D.C. current

B.D. Josephson
1962 (1974)

I immediately set to work to extend the calculation to a situation in which both sides of the barrier were superconducting. The expression obtained was of the form

$$I = I_0(V) + I_1'(V)\cos(\Delta\phi) + I_1(V)\sin(\Delta\phi). \quad (6)$$

As finite voltages the linear increase with time of $\Delta\phi$ implies that the only contribution to the dc current comes from the first term, which is the same as Giaever's



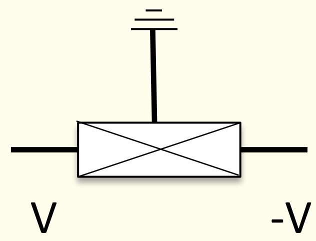
$\Delta\varphi = 2eV\,t$

dc quasiparticle current
odd in V

ac quasiparticle current
odd in V

Josephson ac
even in V

T h r e e - t e r m i n a l   j u n c t i o n

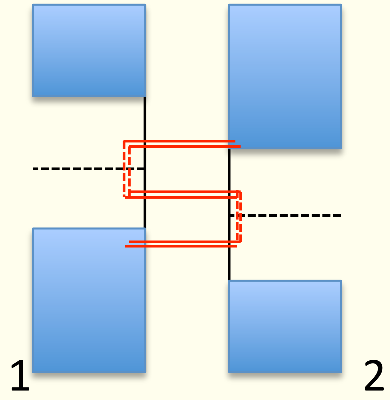


dc quasiparticle currents (MAR)

?

dc quartet current

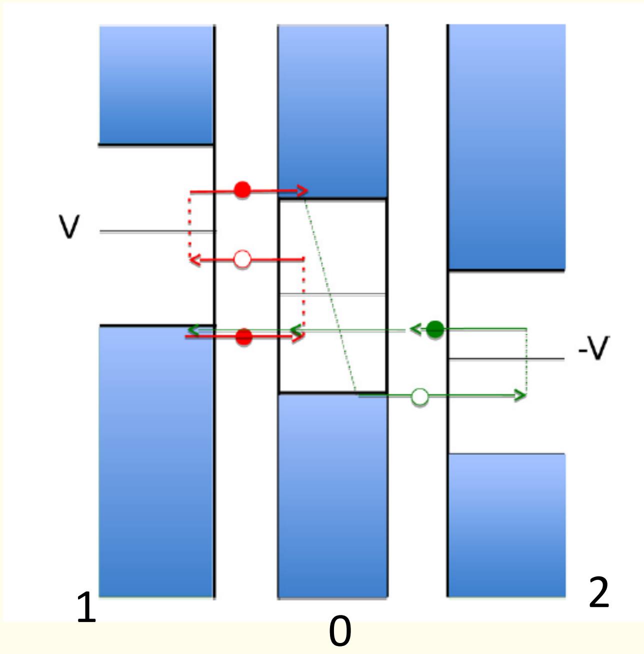
MAR : retracing diagram
probability : $|A_{1\rightarrow 2}|^2$



example of a loop diagram
probability : $|A_{1\rightarrow 0} + A_{1\rightarrow 2\rightarrow 0}|^2$

interference picks up phase $\varphi_1 + \varphi_2$

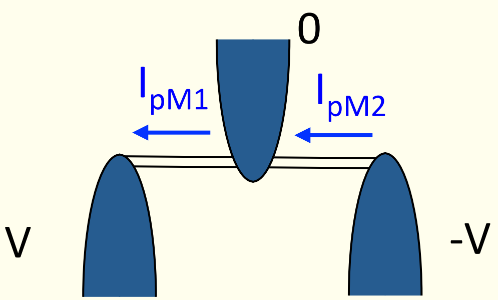
$I_{ph\text{-}MAR} = I_{pM}(V)\ \cos(\varphi_1 + \varphi_2)$

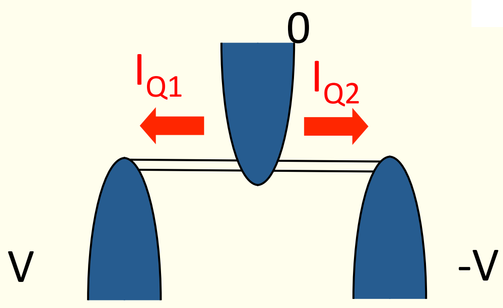


Total current in each terminal :

$$I = I_0(V) + I_{pM}(V)\ \cos(\varphi_1 + \varphi_2) - I_Q(|V|)\ \sin(\varphi_1 + \varphi_2)$$

quasiparticles quartets





$I_{Q1} = I_{Q2}$!

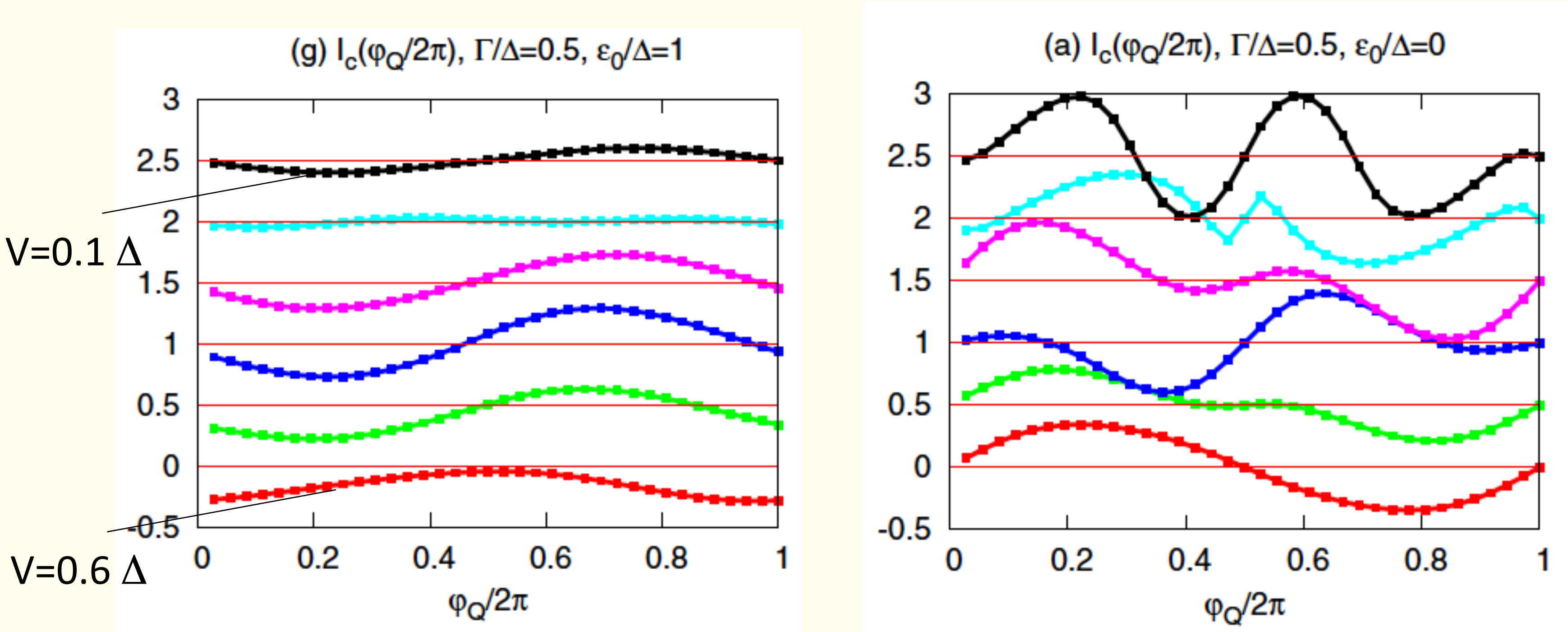
$I_{pM1} \neq -I_{pM2}$

Keldysh Green's function calculations

Tight-binding model (Cuevas method)

Mélin et al. 2016

Single dot-single level junction

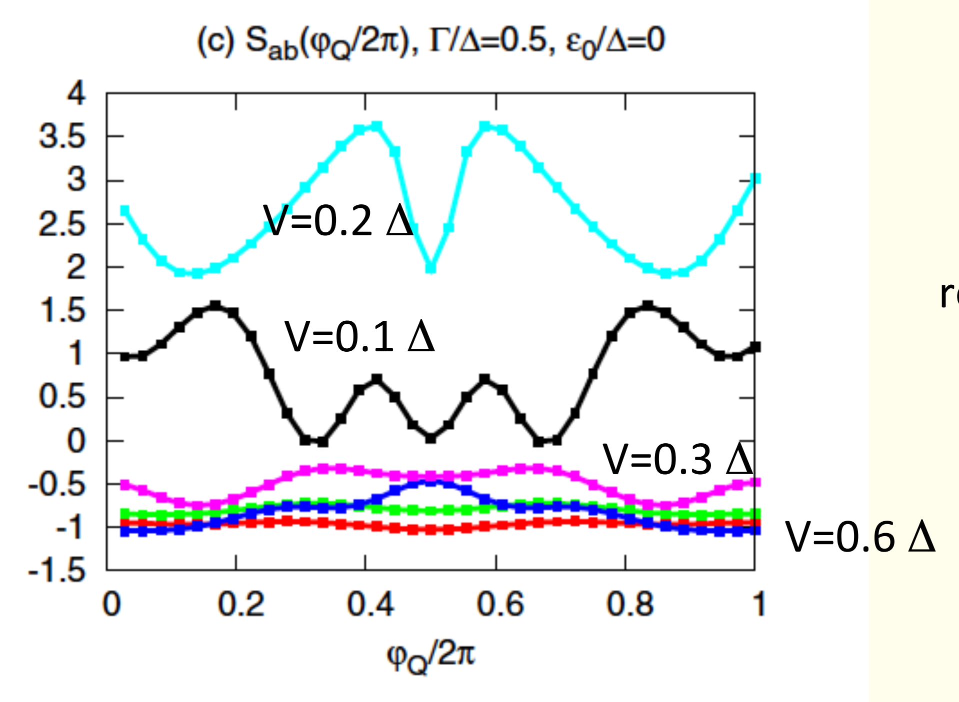


$\varphi_Q = \varphi_1 + \varphi_2$

nonresonant dot

resonant dot

Cross-correlated noise : phase-dependent, positive at small V, non-monotonous in V

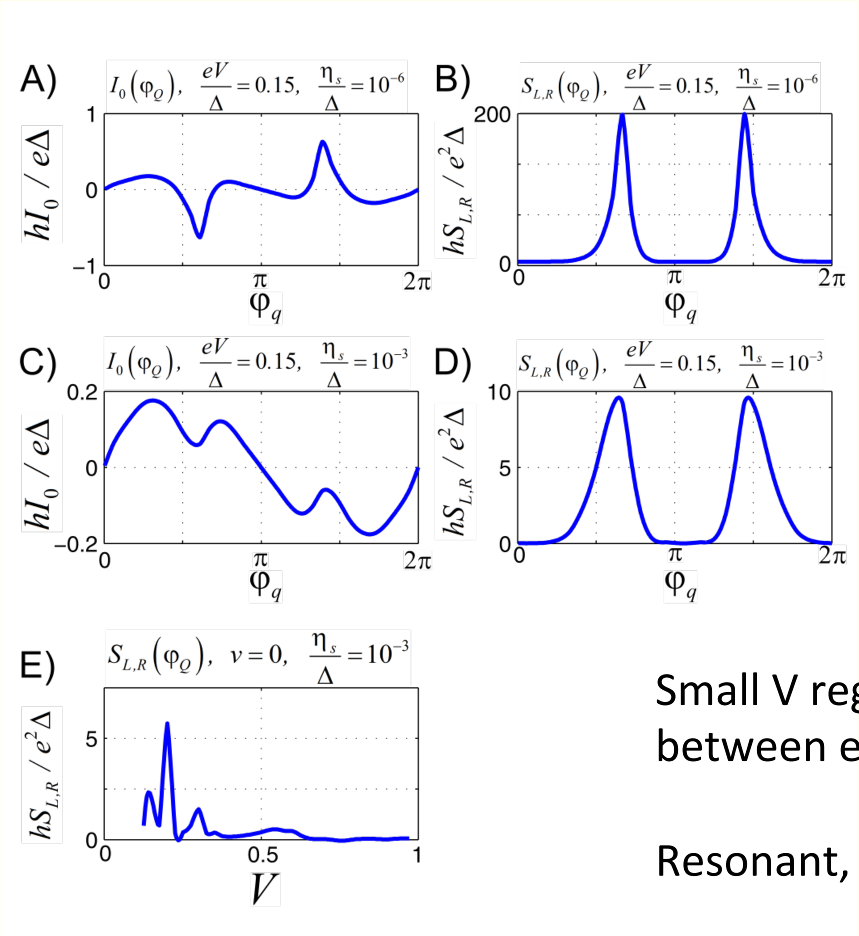


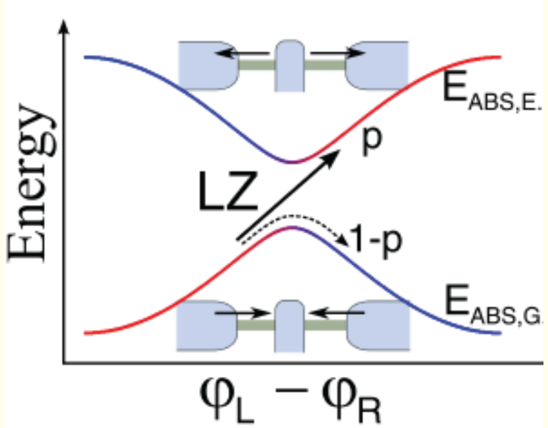
resonant dot

Mélin et al. PRB 2016

Cohen et al., ArXiv 2016

Quartet current   Crossed noise





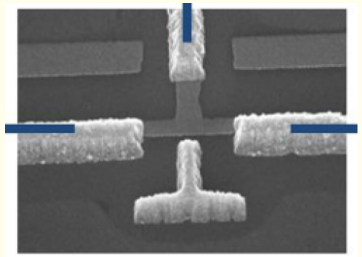
running phase = 4eV t

Small V regime : nonadiabatic transitions between effective Andreev levels

Resonant, current/noise non-monotonous in V

Experiments on quartets

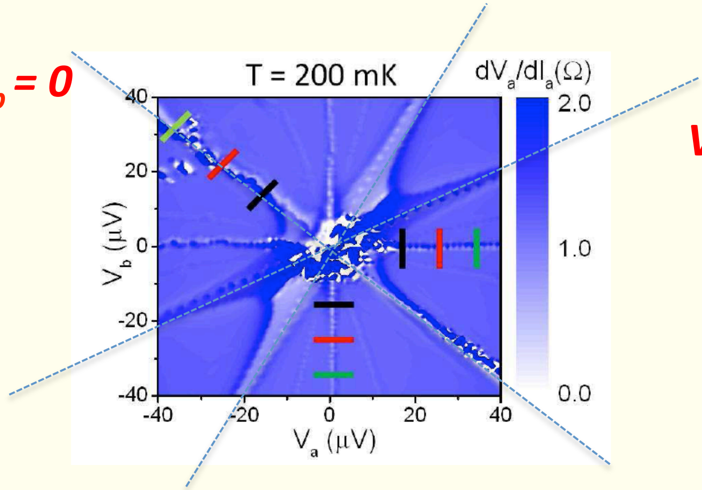
Pfeffer et al. 2014 ***Al-Cu diffusive long junctions*** $E_{Th} < eV << \Delta$

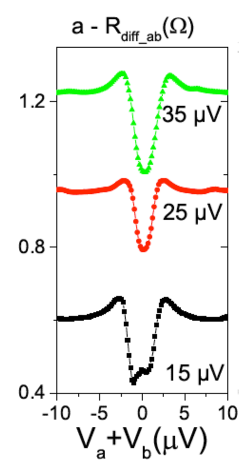


$V_b = 2V_a$

$V_a + V_b = 0$

$V_a = 2V_b$

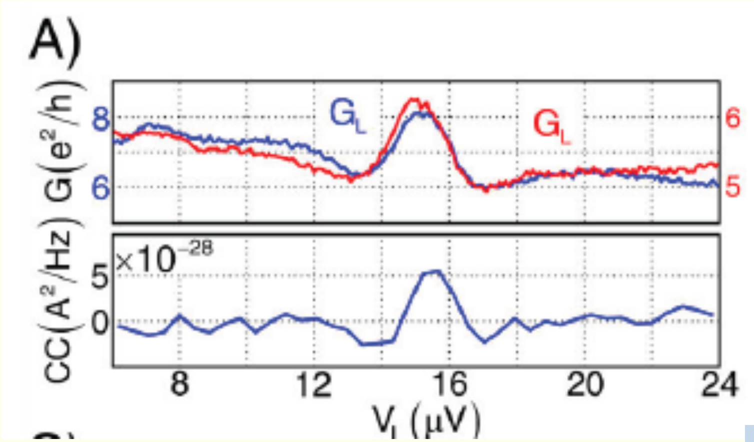


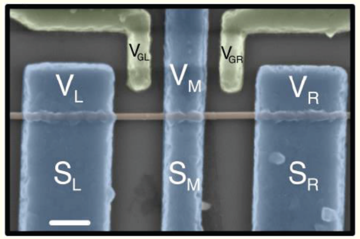


Cohen et al. 2016 ***InAs clean nanowires*** $eV < \Delta < E_{Th}$

Conductance

CC noise

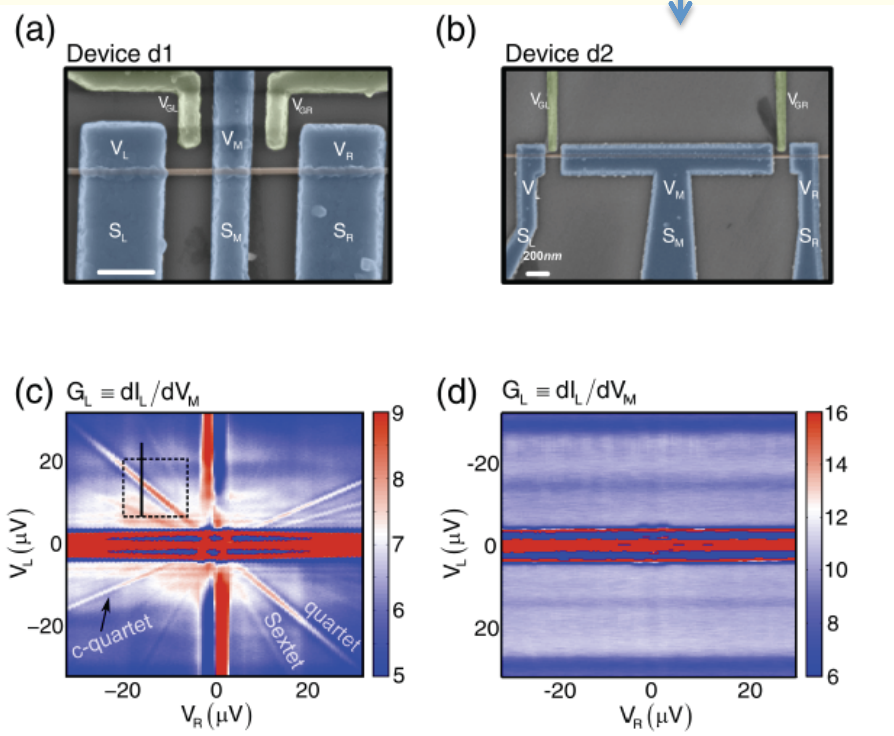




Ruling out an extrinsic synchronization by the circuit environment ?

No effect in a set-up with separated junctions
and SAME electromagnetic environment

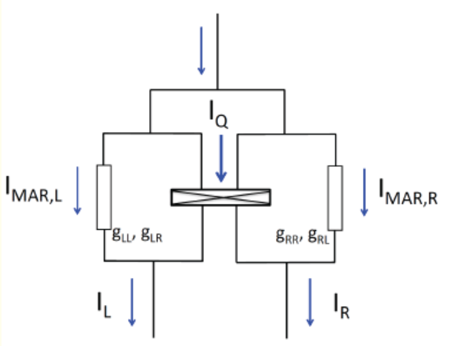
No Cooper pair splitting ←→ No quartets



60 years of experiments on 2T-JJs.... re-done on 3T-JJs ? Not yet !

- Conductance : YES

RSJ interpretation

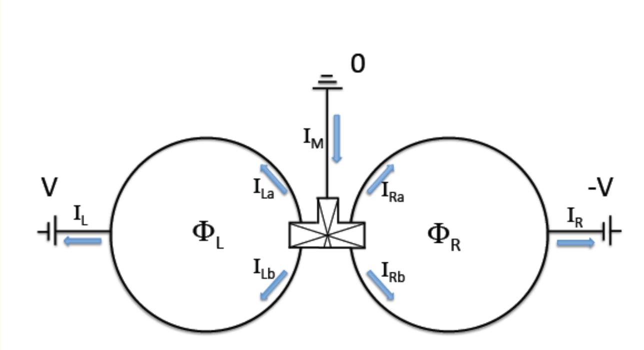


- Gate control, energy filtering : YES

- Positive shot noise : YES
  4e factor in shot noise (instead of 2e) : Not yet

- 4e in Shapiro steps : YES (*Duvauchelle et al. 2016*)

- Phase coherence and interferences : Not yet



- Higher-order pair correlations
  sextets... : YES

Further perspectives and connections

1. Multi-terminal JJs as a platform for topological properties

(Riwar, Houzet, Meyer, Nazarov 2016)

2. Implementation in cold atom BECs :

   role of interactions and confinement
   evidence for 3-body entanglement

Th.

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